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# ESTIMATING AIR VOLUMETRIC FLOW RATE OF OUTDOOR CHEMICAL PLANTS FOR OCCUPATIONAL HEALTH HAZARDS ASSESSMENT

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## ABSTRACT

Performing occupational health hazards assessment is a crucial task in all workplaces, especially in chemical industries. The assessment involves four steps of: hazard identification, toxicity assessment, exposure assessment, and risk characterization. Exposure assessment is the heart in health hazards evaluation. In determining worker's potential exposure, it is essential to estimate exposure concentrations. This can be accomplished if information on the chemicals emission rates and ventilation rates is available. In this paper a method to estimate air volumetric flow rates, Q, for outdoor facilities is proposed. The method was developed based on two variables; the wind speed and the area of the facility. The critical part of the method is to provide the estimates of areas of typical process modules in a chemical plant. Detailed but easy steps on how to perform the Q calculation are provided. The method was tested on six alternative processes to manufacture methyl methacrylate (MMA). For validation purpose, the results were then compared to the actual air flow rates required to maintain the acceptable exposure limits level in the plant. The results indicate that the Q values estimated using the proposed method were more than sufficient. However, bare in mind, the method gives only an estimate value, which is best used for early assessment purpose. The method is applicable to large petrochemical plants.

***Key Words*** : Occupational health, Process design, Exposure assessment

## 1.0 INTRODUCTION

Interests on safety, health and environment (SHE) aspects of a process have been eminently increasing after Trevor Kletz [1] introduced an inherent safety concept. The concept professes that; potentially arising hazards in a process should be identified as early as possible, when it is still in the design stage. Many works have been carried out by academic and industrial researchers regarding safety and environmental risk assessments. Various tools and methods have been developed to help in performing the assessment; ranging from a complex-type, e.g., the Dow Fire and Explosion Index [2] and Mond Index [3], to a simpler-type, namely the Prototype Inherent Safety Index; PIIS [4] and Inherent Safety Index; ISI [5]. Even though the number of research in occupational health assessment is limited, still there are several index-based methods introduced for this reason, notably the Occupational Health Hazard Index; OHHI [6] and Process Route Healthiness Index; PRHI [7].

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Occupational health aspect receives less attention from researchers because it is more complex and it involves not only engineering, but also some medical knowledge. Unlike toxic and acute exposures, which are more of into process safety, occupational health deals with chronic exposure. Chronic toxicity is difficult to quantify because less is known about the long-term effects of chemicals compared to acute toxicity evaluation. Besides, health hazard definitions are less precise and more subjective compared to safety, where hazards related to the physical characteristics of a chemical can objectively defined in terms of testing requirements, e.g., flammability and explosiveness.

Despite its difficulty, the importance of occupational health assessment has been recognized, especially in chemical industries. Basically, assessment of risk to hazards involves four steps:

i. Hazard identification
ii. Toxicity assessment
iii. Exposure assessment
iv. Risk characterization

These are the common procedures taken when carrying out an assessment, but the task becomes trickier if it were to be performed on a process, which is still 'on paper'. The biggest problem encountered is due to the missing of actual data. Many researchers [e.g., 4, 5, 6, 7, 8, 9] highlighted the importance of conducting risk assessment in the design stage, mainly for route-selection process. Their works imply that early stage assessment, though is not totally accurate and precise, but still gives significant benefits in designing and constructing and inherently SHE process.

In occupational health, the heart of the evaluation is the exposure assessment. Exposure assessment is defined as the determination or estimation, qualitatively or quantitatively, of the magnitude, frequency, duration, and route of exposure to a chemical [10]. The goal of exposure assessment it to estimate the concentrations and dosages of chemicals to the populations at risk. From occupational perspective, the target is to assess risk of chemical exposures to the workers in a workplace. Assessments of exposure should cover all modes of exposure and exposure due to activities as well as leaks [11]. Due to the limited information, at preliminary design stage, which is the scope of this paper, only exposure via inhalation due to fugitive emissions as the source of exposure will be addressed. At this stage, process flow diagrams are already generated, but more detailed process documents are still lacking. The approach is reasonable since inhalation is the most important mode of exposure occupationally, especially in chemical industries. As for source of exposure, contribution of worker activities on the exposure can only be covered in the later design stages when more detailed information is available. Major releases due to rupture, large leakage or loss of containment (LOC) will not be discussed because they are more of the safety features.

As previously mentioned, one of the tasks in exposure assessment is to estimate chemical concentrations. This can be accomplished by first, collecting data on the potential amounts of fugitive emissions in the plant. The estimation of fugitive emissions in a proposed plant was well discussed by Hassim and Hurme [12, 13]. Chemicals, upon releases, will enter the atmospheres and being diluted by wind flow. The wind velocity and the area of the plant affect the concentrations of chemicals exposed to the workers. There is plenty of ventilation rates published for indoor facilities, but not for the outdoors. Majority of large petrochemical plants are operating outdoor. Therefore, in this paper, a guideline to estimate air volumetric flow rate of outdoor chemical plants for the purpose of assessing occupational health hazards is proposed. The guideline provides a simple step-by-step methods as well as related values for a quick estimation of the air flow rate.

## 2.0 VENTILATION

Ventilation is mandatory for process plants that are located inside a building. The Workplace (Health, Safety and Welfare) Regulations 1992 require workplaces to be adequately ventilated. ASHRAE Standard 62-1999 [14] defines ventilation as the process of supplying and removing air by natural or mechanical means to and from any space. Generally defined, ventilation is a method of controlling the environment with air flow. It is one of the most important engineering control techniques used to improve or maintain the air quality in the occupational work environment. Basically, industrial ventilation is essential to provide safe, healthful, and comfortable working conditions. Ventilation is of more critical from the occupational health aspect because the concentrations of concern from a health standpoint invariably are orders of magnitude below those of concern for explosive limits. Exposures to atmospheres controlled to concentrations below the explosive limit or even a fraction thereof could cause narcosis, severe illness, or even death [15]. This suggests that ventilation should be focused on the health hazards because if the ventilation can adequately control chemical concentrations at the safe level, generally, it is also sufficient from the safety aspect. Of course, this is not always true for all chemical types. Occupational health also is more crucial since it affects human beings rather than physical properties, which are the major losses due to process safety.

The importance of ventilation is supported by the works that have been carried out for several decades, in which researchers have seen a relation between an inadequate supply of outdoor air and discomfort and illness among building occupants [16]. A study by Seppänen and co-workers [17], which presented a model showing the quantitative relationship between ventilation and work performance concludes that, workers need to breathe fresh air in order to perform well. The studies revealed typically a 1 to 3 % improvement in average performance per 10 L/s/person increase in outdoor air ventilation rate.

For an indoor facility, general ventilation is applicable for health hazard control, but it has four limiting factors [15]:

i. The quantity of contaminant generated must not excessive, or the air volume necessary for dilution would be prohibitively large;
ii. Workers must be far enough away from evolution of the contaminant or the contaminant must be of sufficiently low concentration, so the workers will not be exposed to excessive levels;
iii. The toxicity of the contaminant must be relatively low; and
iv. The evolution or generation of the contaminant must be reasonable, uniform, and consistent.

## 3.0 CHEMICAL DILUTIONS IN OUTDOOR FACILITIES

For outdoor facilities, basically reduction of exposures is achieved by natural means. Since the operations are not enclosed and workers are not within a confined area, chemicals released to the atmospheres are regularly diluted adequately by natural wind flow. This is part of the reasons why most of the petrochemical plants are built outdoor. The siting of plant in the open air rather than in a building is often the most effective means of ventilation, since small leaks will be dispersed by winds [11].

For indoor facilities, the ventilation requirement is expressed in terms of ventilation rates. Ventilation rates are commonly given in units of liters per second (L/s) or, alternatively, cubic feet per minute (cfm), or as air change rates in units of air changer per hour ($h^{-1}$). There are many guidelines published as the recommended ventilation rates, depending on the aim of the ventilation, volume of space, number of workers and types of operations involved. If the actual ventilation rate is unknown, for the purpose of conducting assessment, a rate of 3000 cfm may be considered typical and 500 cfm represents the worst case [10]. Meanwhile, workplace general ventilation rates are normally between 0.2 and 30 mixing air changers per hour [18].

Nevertheless, publications relating to air volumetric flow rates in outdoor facilities are always inconsistent. Clement Associates [19] however, suggest 26 400$\upsilon$ $ft^3$/min as the ventilation rate for outdoor operations with only minimal structure, where $\upsilon$ is the wind speed in miles per hour (mph). The estimate proposed by Clement Associates indicates that for outdoor processes, the air volumetric flow rate is a function of two variables: the wind speed and the area of the facility.

This paper presents a method for calculating air volumetric flow rates within a chemical plant. The rates are useful in estimating potential exposures to workers, before an assessment on overall health hazards risk can be carried out.

## 4.0 ESTIMATION OF AIR VOLUMETRIC FLOW RATE

### 4.1 Establishing Required Data

In this paper, the air volumetric flow rate of outdoor facilities, Q, is estimated based on the two variables mentioned above; the wind speed, $\upsilon$, and the area of the facility, A. Concentrations of chemicals may be higher in a denser area, located in an area with a lower wind speed and vice versa. In general, Q can simply be calculated from the equation below:

$$Q = \upsilon \times A \tag{1}$$

In reality, wind speed varies with location and time. The best approach is to use local wind distribution data because this will results in a Q value that represents the actual condition where the plant is located. However, for simplification, an average wind speed can be assumed to be 9 mph, which equals to 4 m/s. This is a typical speed used to describe outdoor wind condition [e.g., 19, 20, 21].

The critical part in calculating Q is to estimate total area of the facility, A. It is not making sense to propose a single value of A since each plant has unique area, depending on types of operations run in the plant. Therefore, the floor areas of common process modules in chemical plants were estimated, instead. Process modules refer to standard unit operations in a chemical plant. Data on the floor areas enables the total area of the overall plant to be calculated. Different plant has different type and number of modules, hence indirectly affecting the area of the facility. The area of the module is estimated based on the actual plant layout of typical chemical processes. For better reliability, the area is calculated for several units of the same module type, before taking the average value to represent the area of particular module.

The area of module presented in Table 1 has already taking into account the 'spacing' factor in a plant. Although the spacing factors was not precisely addressed due to data lacking, this will not affect the usability and reliability of the Q calculated since the main goal is to estimate the maximum possible concentrations in the plant (worst-case scenario).

**Table 1** Area of Different Process Module Type

| Module | Area ($m^2$) |
|---|---|
| Liquid-liquid Extractor | 48.0 |
| Flash | 72.2 |
| Distillation | 129.2 |
| Stripper | 146.8 |
| Compressor | 182.2 |
| Absorber | 81.7 |
| Continuous Stirred Tank Reactor (CSTR) | 95.2 |
| Tubular Reactor (PFR) | 108.3 |
| Ion Exchanger | 28.3 |

## 4.2 Testing Data Reliability

The reliability of the module's floor areas calculated was investigated by comparing them to the number of leak points in equipment. Since the research focuses on occupational aspect, the leak points of interests are those with potential fugitive emissions, e.g., flanges, pump seals, valve stems, and compressor shafts. Even though the quantity is small, prolonged exposures to fugitive emissions may develop occupational diseases among the exposed workers. Generally, larger module has more leaking points due to the installation of more piping fittings compared to the smaller one. Table 2 shows the number of sources of fugitive emissions in process modules and Table 3 demonstrates the correlation between module area and number of leak points.

**Table 2** Number of Leak Points in Process Module

| Module | Valve | Pump | Flanges | Sampling Pt | Compressor | Agitator | Total Leak Pts |
|---|---|---|---|---|---|---|---|
| Absorber | 43 | 2 | 113 | 3 | 0 | 0 | 161 |
| Stripper | 72 | 2 | 182 | 2 | 0 | 0 | 258 |
| Distillation Column | 53 | 6 | 155 | 2 | 0 | 0 | 216 |
| Flash Column | 40 | 2 | 87 | 0 | 0 | 0 | 129 |
| Liq-liq Exchanger | 44 | 2 | 95 | 3 | 0 | 0 | 144 |
| CSTR | 71 | 2 | 188 | 3 | 0 | 1 | 265 |
| PFR | 66 | 2 | 162 | 2 | 0 | 0 | 232 |
| Ion Exchanger | 17 | 0 | 40 | 0 | 0 | 0 | 57 |
| Compressor | 18 | 0 | 65 | 0 | 1 | 0 | 84 |

From Table 3, the area corresponds well to the number of leak points for all modules except for CSTR and compressor. Further analysis was carried out to find out the relation between module's area, number of leaking points, and amount of emissions. Previously, total fugitive emissions from each module were estimated based on the Average Emission Factor Approach [22]. For each type of module, number of leak points per $m^2$ area and emission rates per $m^2$ area as well as per leak point were calculated and summarized in Table 4.

**Table 3** Correlation between Area and Number of Leak Points

| Module | Area (m2) | Rank | Total Leak Points | Rank |
|---|---|---|---|---|
| Liq-Liq Extractor | 48.0 | 8 | 144 | 6 |
| Flash | 72.2 | 7 | 129 | 7 |
| Distillation | 129.2 | 3 | 216 | 4 |
| Stripper | 146.8 | 2 | 258 | 2 |
| Compressor | 182.2 | 1 | 84 | 8 |
| Absorber | 81.7 | 6 | 161 | 5 |
| CSTR | 95.2 | 5 | 265 | 1 |
| PFR | 108.3 | 4 | 232 | 3 |
| Ion Exchanger | 28.3 | 9 | 57 | 9 |

**Table 4** Total Fugitive Emission Rates from Process Modules

| Module | Total Emissions kg/h | Leak Points/$m^2$ $m^{-2}$ | Emissions/$m^2$ kg/h.$m^2$ | Emissions/Leak Point kg/h |
|---|---|---|---|---|
| Liq-liq Exchanger | 0.44 | 3 | 0.009 | 0.003 |
| Flash | 0.38 | 2 | 0.005 | 0.003 |
| Distillation | 0.66 | 2 | 0.005 | 0.003 |
| Stripper | 0.72 | 2 | 0.005 | 0.003 |
| Compressor | 0.45 | 0.5 | 0.002 | **0.005** |
| Absorber | 0.48 | 2 | 0.006 | 0.003 |
| CSTR | 0.73 | 3 | 0.008 | 0.003 |
| PFR | 0.69 | 2 | 0.006 | 0.003 |
| Ion Exchanger | 0.14 | 2 | 0.005 | 0.003 |

The results show that, for a module with three leak points/$m^2$, the emission rates range from 0.008 to 0.009 kg/h.$m^2$, whereas if there are two points/$m^2$, the rates are between 0.005 to 0.006 kg/h.$m^2$. In overall, all modules emit 0.003 kg/h of fugitive emissions per single leak source except for compressor. As for compressor, the amount of fugitive emissions per leak point is almost as the amount emitted from two points in other modules. The reason is, emission from compressor's shaft is relatively larger than from other piping components (e.g., emission factor for a compressor's shaft is 0.228 kg/h compared to only 0.00183 kg/h for a flange). This explains why compressor emits larger amount of fugitive emissions despite of a relatively small number of leak points it has.

The analysis performed above indicates that the areas estimated for the modules are considerably reliable since they show a good correlation with other estimated data of the modules, such as the number of leak points in and the rates of emission from the modules.

### 4.3 Estimation Steps

Since reliability analysis of the module area gave a satisfactory result, Q can subsequently be calculated according to the following steps:

*Step i* : Count number of each type of process module in the plant;
*Step ii* : Based on the guideline given in Table 1, total up the areas of all modules identified in Step i, $\Sigma A_i$.
*Step iii* : By assuming the plant's floor area is square, calculate the wide of the area, $s = \sqrt{\sum A_i}$
*Step iv* : Calculate the vertical area of the plant, $A_n = s \times h$, where h is the average height. For large petrochemical plants, assume $h = 7\ m$; a height where majority of the piping components below this level [23].
*Step v* : Finally, calculate the air volumetric flow rate of the plant, $Q = \upsilon \times A_n$, where $\upsilon$ is the wind velocity.

## 5.0 CASE STUDY

The method is tested on the methyl methacrylate (MMA) process case study. This case study has been widely used to illustrate safety, health and environmental assessment indices for application during the chemical design phase. The extensive studies that have been performed make available considerable amount of essential data, hence making the case study more attractive to be used. Basically, there are six common process options for manufacturing MMA. These process routes are different from each other in terms of the reactants and the operating conditions, as well as the number and types of process modules employed. The potential process candidates are:

i. Acetone cyanohydrin based route (ACH)
ii. Ethylene via methyl propionate based route (C2/MP)
iii. Ethylene via propionaldehyde based route (C2/PA)
iv. Propylene based route (C3)
v. Isobutylene based route (i-C4)
vi. Tert-butyl alcohol based route (TBA)

### 5.1 Results and Discussions

Air volumetric flow rate, Q was calculated for the overall plant (one Q value per plant). As discussed by Gupta and Edwards [24], for the ACH based route, only the steps that are related to the actual production of MMA are considered. The steps relate to the production of the basic material and the disposal of byproducts are excluded; so that this route will be assessed on the same basis as the other remaining five routes. The calculation of Q was performed on all the alternative routes based on the steps described previously. The calculation steps and the results are summarized in Table 5.

The results show that the C2/PA route has the largest air flow rate, Q, due to the largest area this process has. The C3 route has the second largest Q after the C2/PA. However, it is not our interest to rank the quantity of flow rate of different processes. In fact, there is no particular reason of doing because no conclusion can be drawn from such observation. Nevertheless, the tabulated results can be compared to the process area and total number of leak points in the process in order to see the relation between these variables.

**Table 5** Summary of Q Calculation Steps and Results

| | | | | | *Step i* | | | | | *Step ii* | *Step iii* | *Step iv* | *Ste* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Process** | **LLEX** | **Flash** | **Dist** | **Strip** | **Comp** | **Abs** | **CSTR** | **PFR** | **Ion Exc** | **$\Sigma A_i (m^2)$** | **s (m)** | **$A_n (m^2)$** | **Q (n** |
| ACH | 1 | 0 | 4 | 1 | 0 | 0 | 3 | 0 | 0 | 997 | 32 | 221 | 8 |
| C2/MP | 0 | 2 | 7 | 0 | 1 | 0 | 0 | 3 | 0 | 1556 | 39 | 276 | 11 |
| C2/PA | 2 | 3 | 8 | 1 | 1 | 1 | 2 | 2 | 0 | 2164 | 47 | 326 | 13 |
| C3 | 1 | 0 | 8 | 0 | 1 | 0 | 1 | 3 | 0 | 1684 | 41 | 287 | 11 |
| i-C4 | 2 | 2 | 5 | 1 | 0 | 1 | 1 | 2 | 0 | 1426 | 38 | 264 | 10 |
| TBA | 2 | 2 | 5 | 1 | 0 | 1 | 1 | 2 | 0 | 1426 | 38 | 264 | 10 |

LLEX:Liquid-liquid exchanger; Dist:Distillation; Strip:Stripper; Comp:Compressor; Abs:Absorber; Ion Exc:Ion Exchanger

Figure 1 demonstrates the Q value, process area, and total leak points of all the six candidate processes. The figures are presented in a normalized form to allow for better comparison. As for the two routes with the two largest Q values (C2/PA and C3), the flow rates, Q correlate well with the total number of leak points in both processes. The i-C4 and TBA processes have similar Q value since they are the same, except for the primary reactants. The correlations between Q and number of leak points for i-C4 and TBA, as well as the C2/MP routes are slightly mismatch, but still within acceptable pattern.

These Q values are higher than those suggested by the Clement Associates [19], mainly due to the size of the plant (affected indirectly by the number of equipment installed in the plant). As previously stated, the outdoor ventilation rate provided by the Clement Associates valid for facilities with minimal structure, whereas in this paper, Q was calculated for large petrochemical plants (the case study). However, in order to ensure if the Q values obtained for each process can sufficiently control the concentrations of chemicals at their tolerable exposure limits, further validation analysis was conducted.

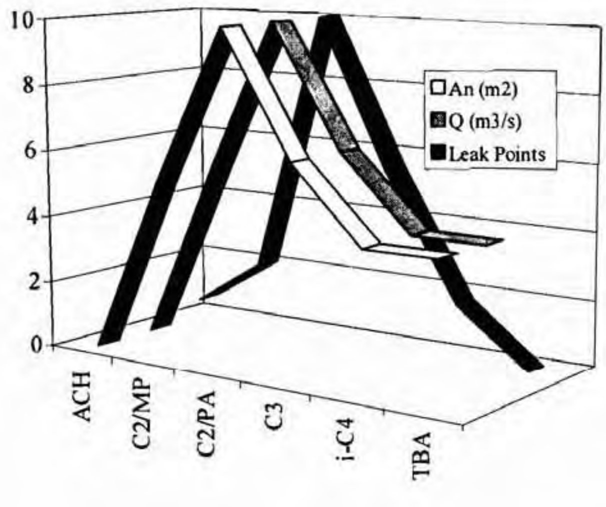


**Figure 1** Summary of the Normalized Results

## 5.2 Validation of the Q Calculation

The confirmation investigation was carried out by calculating the flow rate of air necessary to maintain the level of chemicals at their safe exposure limits. This was done by assuming that fugitive emission was the only source for worker's exposure. The assumption is valid for the purpose of assessing routine occupational health hazards exclusively. Besides, this is a common scenario in a standard plant, operating within normal conditions. For each route, the chemicals present were identified. Then, their potential rate of fugitive emissions was determined based on the process flow diagrams [12, 13].

Average Emission Factor Approach, which is suitable for estimating fugitive emissions during the design stage, gives the emissions in a mass rate unit. The mass flow rate of the chemicals, FE, were converted into volumetric flow rate, q. In prior, the vapor density of the chemicals was first determined based on the ideal gas law. Then, the actual air flow rate, $q_{air}$ required to meet the exposure limits was calculated. Finally, the required $q_{air}$ was compared to the Q values. The summaries of the validation tasks are presented in Table 6.

Based on the comparison between $q_{air}$ and Q values, the actual air flow rates ($q_{air}$) required to maintain concentrations of the chemicals at the safe level are well below the Q estimated. For several chemicals with no exposure limit data, the chemicals should not be omitted from the assessment; instead, they should be listed together with the other chemicals so that their presence within the working environment is being aware of. In this paper also, several validation procedures were carried out. The reason is; risk assessment, even though should be based on solid scientific facts, but by the definition itself, it also always depends on the reliability of the facts on the exposure [25].

The results confirm that the Q calculated is adequate to prevent the risks of occupational health hazards for all process routes in the case study. In fact, the Q is well above the minimum requirement of the actual air flow rate (the Q is sufficient even if safety factor of 10 is applied). This indirectly indicates that the method and values proposed in this paper for Q calculation are considerably acceptable. However, it is not necessary for users to perform the validation process since the work was quite tedious. The results of the validation, as presented in this paper are convincing enough to support the usage and application of the Q estimation method.

## 6.0 CONCLUSION

The proposed method can be used to calculate the air volumetric flow rate of outdoor chemical plants during the design stage. The flow rate is a crucial data, required for estimating exposures to workers within workplaces. The motivation for developing the method was due to the limited literatures available regarding this subject, compared to the abundant values published for indoor ventilation rates. Besides, this information is required for assessing the risk of occupational health hazards.

The method was applied on six process routes for the production of methyl methacrylate. The results show that the flow rate depends mainly on the area of the facility since a consistent wind velocity was used in the calculation. The air flow rate, Q, was also compared to the total number of leak points in the process in order to confirm the reliability of the results obtained. The correlation shows a good overall agreement between these variables; hence it implies a significant validity of the results.

**Table 6** Validation of Q Values

| Process | Chemical | Total FE g/min | q $m^3/s$ | EL ppm | $q_{air}$ $m^3/s$ | Q $m^3/s$ |
|---|---|---|---|---|---|---|
| C2/MP | Carbon monoxide | 9 | 1.36E-04 | 31 | 4 | 1104 |
| | Methyl propionate | 24 | 1.12E-04 | 83 | 1 | |
| | Methanol | 28 | 3.57E-04 | 206 | 2 | |
| | Methyl methacrylate | 19 | 7.60E-05 | 10 | 7 | |
| | Methylal | 2 | 1.20E-05 | 1029 | 0 | |
| C2/PA | Carbon monoxide | 11 | 1.62E-04 | 31 | 5 | 1302 |
| | Propionaldehyde | 25 | 1.78E-04 | 19 | 9 | |
| | Methacrolein | 22 | 1.28E-04 | 8 | 15 | |
| | Methacrylic acid | 14 | 6.85E-05 | 20 | 3 | |
| | Hexane | 25 | 1.19E-04 | 512 | 0 | |
| | Acetic Acid | 10 | 6.85E-05 | 5 | 13 | |
| | Methyl methacrylate | 23 | 9.22E-05 | 10 | 9 | |
| | Methanol | 10 | 1.33E-04 | 206 | 1 | |
| | Formaldehyde | 2 | 3.04E-05 | 0 | 101 | |
| C3 | Hydrogen fluoride | 15 | 3.12E-04 | 2 | 170 | 1149 |
| | Isobutyl fluoride | 15 | 6.69E-05 | NA | Isobutyl fluoride | |
| | Isobutyric acid | 16 | 7.25E-05 | 8 | 9 | |
| | Methacrylic acid | 9 | 4.32E-05 | 20 | 2 | |
| | Methyl methacrylate | 29 | 1.20E-04 | 10 | 12 | |
| | Methanol | 10 | 1.33E-04 | 206 | 1 | |
| | Propylene | 7 | 6.55E-05 | 500 | 0 | |
| i-C4 | Isobutylene | 1 | 7.10E-06 | NA | Isobutylene | 1058 |
| | Methacrylic acid | 11 | 5.10E-05 | 20 | 3 | |
| | Hexane | 25 | 1.19E-04 | 512 | 0 | |
| | Acetic acid | 12 | 8.09E-05 | 5 | 15 | |
| | Methyl methacrylate | 23 | 9.22E-05 | 10 | 9 | |
| | Methanol | 10 | 1.33E-04 | 206 | 1 | |
| | Methacrolein | 8 | 4.75E-05 | 8 | 6 | |
| TBA | Tert-butyl alcohol | 1 | 5.37E-06 | 100 | 0 | 1058 |
| | Methacrolein | 8 | 4.75E-05 | 8 | 6 | |
| | Methacrylic acid | 11 | 5.28E-05 | 20 | 3 | |
| | Hexane | 25 | 1.19E-04 | 512 | 0 | |
| | Acetic acid | 10 | 6.85E-05 | 5 | 13 | |
| | Methyl methacrylate | 23 | 9.22E-05 | 10 | 9 | |
| | Methanol | 10 | 1.33E-04 | 206 | 1 | |
| ACH | Hydrogen cyanide | 2 | 2.61E-05 | 5 | 6 | 884 |
| | Acetone cyanohydrin | 17 | 8.35E-05 | 1 | 58 | |
| | Methacrylamide | 11 | 5.13E-05 | NA | Methacrylamide | |
| | Methanol | 10 | 1.33E-04 | 206 | 1 | |
| | Methyl methacrylate | 33 | 1.32E-04 | 10 | 13 | |
| | Acetone | 1 | 1.03E-05 | 506 | 0 | |

FE: Fugitive emission rate; EL: Exposure limits (either local or international regulation, e.g. TLV)

The Q values were then compared to the actual air flow rate required for maintaining chemicals concentration within the workplace atmospheres at their safe exposure levels. The results show that the Q calculated for all the six processes meets the requirements well.

The method cannot and is not intended to give a highly accurate result, because at the preliminary design stage, with a flow diagram as the only process data available, much data are still unknown. However, it provides a simple guideline, to swiftly get the brief idea on air volumetric flow rate within an outdoor plant, which is later useful when assessing the potential occupational exposures and health hazards. This method is applicable to large petrochemical plants and is practical for process assessment during the early stage of preliminary design.

## REFERENCES


[1] Kletz, T. A. 1991. *Plant Design for Safety - A User-friendly Approach*, New York: Hemisphere Publishing Corporation.

[2] Dow Fire and Explosion Index. 1987. *Hazard Classification Guide*, 6th ed., Midland, MI: Dow Chemical.

[3] Mond Index. 1993. *Mond Index Services*, Northwich, UK.

[4] Edwards, D. W. and D. Lawrence. 1993. Assessing the Inherent Safety of Chemical Process Routes: Is There a Relation Bbetween Plant Costs and Inherent Safety?, *Process Safety and Environmental Protection*, 71(B4): 252-258

[5] Heikkilä, A.-M., M. Hurme and M. Järveläinen. 1996. Safety Considerations in Process Synthesis, *Computers Chem. Engng.*, 20(A): S115-S120

[6] Johnson, V. S. 2001. *Occupational Health Hazard Index for Proposed Chemical Plant*, Loughborough University: MSc Thesis.

[7] Hassim, M. H. and D. W. Edwards. 2006. Development of a Methodology for Assessing Inherent Occupational Health Hazards, *Process Safety and Environmental Protection*, 84(B5): 378-390

[8] Hassim, M. H., D. W. Edwards and M. Hurme. 2006. Assessing the Inherent Occupational Health Hazards During the Conceptual Design Phase, *Chemical Engineering Transactions*, 9: 119-124

[9] Hassim, M. H., M. Grönlund and M. Hurme. 2008. Inherent EHS Considerations in Process Development, *Chemical Engineering Transactions*, 13: 295-302

[10] Lipton, S. and J. Lynch. 1994. *Handbook of Health Hazard Control in the Chemical Process Industry*, U. S. A: John Wiley and Sons.

[11] Lees, F. P. 1996. *Loss Prevention in the Process Industries: Hazard Identification, Assessment & Control*, 2nd ed., Oxford: Butterworth-Heinemann.

[12] Hassim, M. H. and M. Hurme. 2008. Computer Aided Design of Occupationally Healthier Processes, *Computer Aided Chemical Engineering*, 25: 1119-1124

[13] Hassim, M. H. and M. Hurme. 2008. Quantification of Fugitive Emissions For Proposed Chemical Plants, *AIChE 100th Annual Meeting*, (16-21 November), Philadelphia, USA.

[14] ASHRAE. 1999. *Ventilation for Acceptable Indoor Air Quality*, ASHRAE Standard 62-1999, Atlanta: American Society of Heating, Refrigeration and Air-Conditioning Engineers.

[15] Harris, R. L. 2000. *Patty's Industrial Hygiene*, 5th ed., Volumes 1-4, U. S. A: John Wiley & Sons.

[16] Manuel, J. 2006. Will Work for Air, *Environmental Health Perspectives*, 114(6): A345

[17] Seppänen, O., W. J. Fisk and Q. H. Lei. 2006. Ventilation and Performance in Office Work, *Indoor Air*, 16: 28-36

[18] Jayjock, M. A. 1997. Uncertainty Analysis in the Estimation of Exposure, *American Industrial Hygiene Association Journal*, 58(5): 380-382

[19] Clement Associates. 1982. *Methods for Estimating Workshop Exposure to PMN Substances*, USEPA Contract 68-01-6069.

[20] CCPS. 2000. *Guidelines for Chemical Process Quantitative Risk Analysis*, 2nd ed., New York: AIChE.

[21] Baldwin, P. E. J. and A. D. Maynard. 1998. A Survey of Wind Speeds in Indoor Workplaces, *Ann. Occup. Hyg.*, 42(5): 303-313

[22] EPA. November 1995. *Protocol for Equipment Leak Emission Estimates*, Publ. No. EPA-453/R-95-017, North Carolina: Emission Standards Division.

[23] Mecklenburgh, J. C. 1985. *Process Plant Layout*, UK: George Godwin.

[24] Gupta, J. P. and D. W. Edwards. 2003. A Simple Graphical Methodology for Measuring Inherent Safety, *Journal of Hazardous Materials*, 104(1-3): 15-30

[25] Ahlberg, R. W. 1999. Risk Assessment and Risk Communication in Chemical Exposure, *Int. Arch. Occup. Environ. Health*, 72(3): M11-M13